Probabilistic Seismic Design and Evaluation of Nuclear Facility Structures

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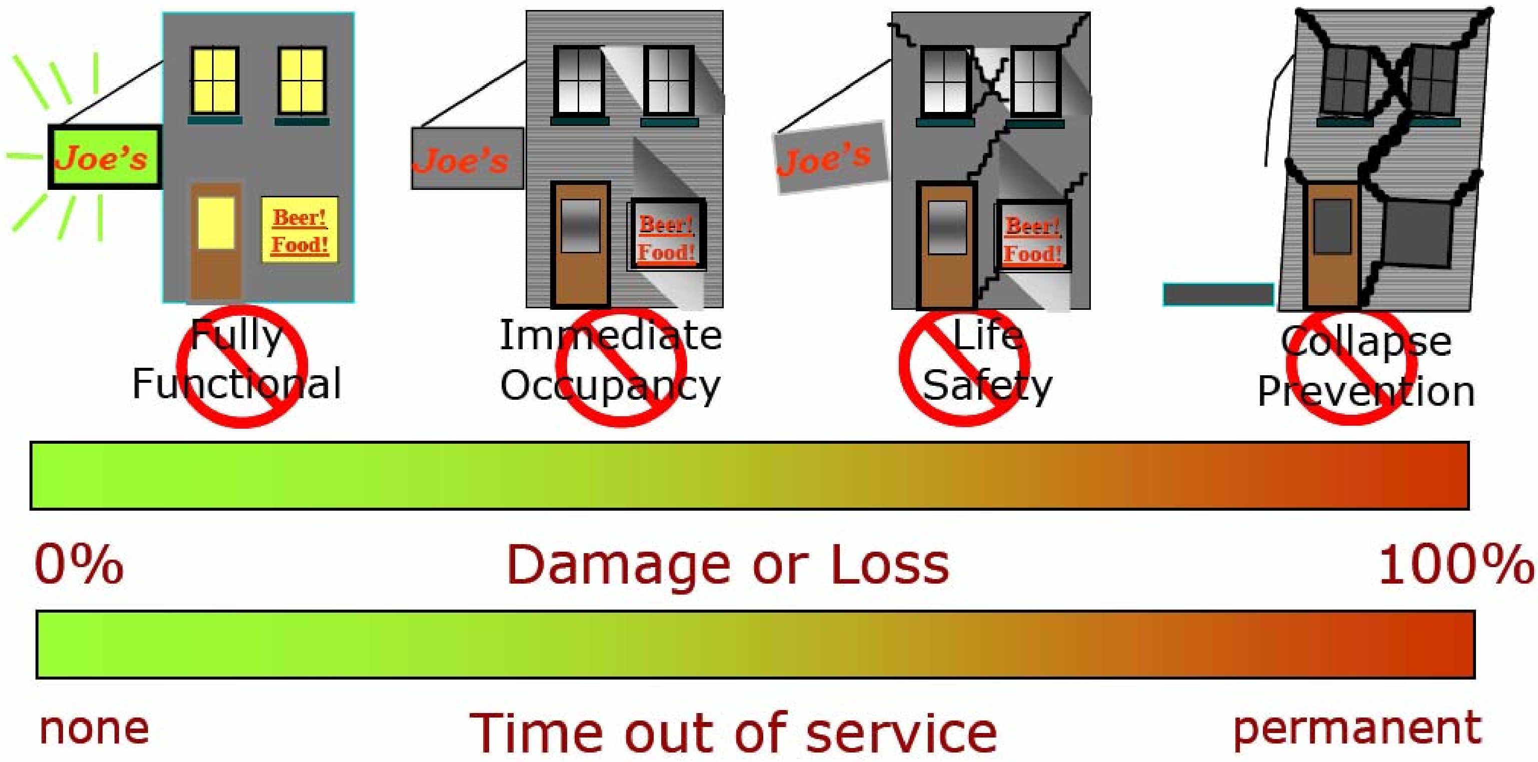
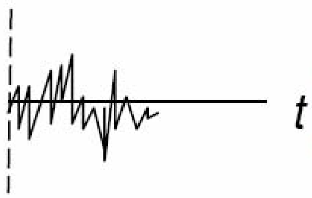
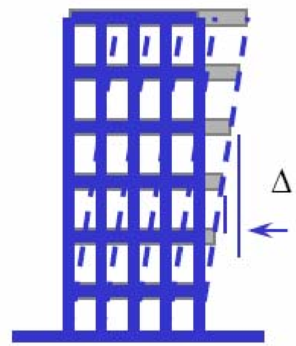
Performance-Based Design



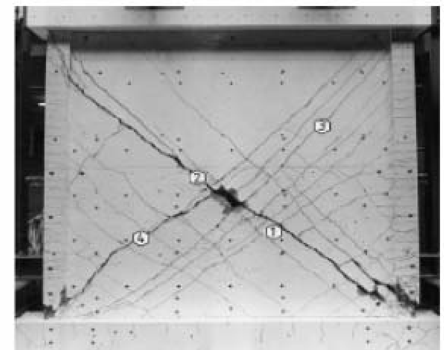
Probabilistic Approach



Ground motion



Structural response



Damage

Performance metrics

Probabilistic framework with explicit consideration of uncertainty

Goals and Benefits

- Improve prescriptive code requirements
  - Beneficial all building types and all stakeholders
- Characterize the potential consequences of building response to earthquakes by estimating:
  - Direct economic loss: repair and replacement costs
  - Indirect economic loss: business interruption
  - Casualties: deaths and injuries
- Enable design for:
  - Better performance of critical facilities
  - Greater confidence in better performance through using new structural protection concepts, such as base isolation
  - Equivalent performance (wrt. code) but at lower cost and with higher confidence

Common Probabilistic Basis for Evaluation of Structures

- Given a seismic hazard environment and a structure, the probability that a performance objective is achieved is:

$$P_{PO} = \int_{hazard} P(PO \mid hazard)\, d(hazard)$$

- Must consider probability distributions of seismic hazard, of demand and of capacity due to:
  - Lack of knowledge (epistemic uncertainty)
  - Record-to-record randomness (aleatory uncertainty)

Seismic Hazard

- Use a ground motion intensity measures (PGA, Sa(T1), etc.)
- Probability of exceeding a value of ground motion intensity (hazard curve):

$$P_H = H(s_a^{P_H}) = k_0 (s_a^{P_H})^{-k}$$

- An earthquake does not know if the structure is conventional or nuclear: seismic hazard is the same

Probability of Failure

- A comparison demand and capacity:

$$P_F = P(C \leq D) = \int_{s_a} P(F \,|\, s_a) \,|dH(s_a)|$$

- Key assumptions about hazard, demand and capacity probability distributions:
  - Log-normal
  - Dispersion β about the median

DOE-1020 and ASCE 43-05: Acceptance Criteria

- Probability of failure is smaller than probability of hazard
- Risk reduction ratio at the structure level

$$R_R = \frac{P_H}{P_F}$$

Performance Category	Risk Reduction Ratio
PC-1 (conventional)	R_R=1.0
PC-2 (internal exposure risk)	R_R=1.0
PC-3 (labs, fuel cycle facilities)	R_R=10.0
PC-4 (experimental reactors)	R_R=20.0

Conventional Design: Acceptance Criteria

- Probability of failure is, implicitly, assumed equal to the probability of hazard
- Design equation: ϕ
  - Capacity reduction γ
  - Demand amplification

  at the structural element level

$$P_F = P_H$$

$$\phi C > \sum \gamma D$$

Two Formats: Unified

Probability of Hazard	$P_H = k_1 \left(S_a^{P_H} \right)^k$	
IM Based Probability of Failure	$P_F = k_1 \left(\eta_{S_a,C} \right)^{-k} e^{\frac{1}{2}(k \beta_C)^2}$	
PSDM Based Probability of Failure	$P_F = H_{S_a} \left(S_a^{\eta_C} \right) e^{\frac{1}{2}\frac{k^2}{b^2} \beta_{D \mid S_a}^2} e^{\frac{1}{2}\frac{k^2}{b^2} \beta_C^2}$	
	Hazard Format	**DFCD Format**
Design/Assessment Equation	$R_R = \frac{P_H}{P_F}$	$\varphi \cdot \mathbf{C} \geq \gamma \cdot \mathbf{D}$
IM Based Assessment	$R_R = \left(\frac{^{P_o}S_a}{\eta_{S_{a,C}}} \right)^{-k} e^{-\frac{1}{2}(k \beta_{S_a,C})^2}$	$\underbrace{^{P_o}S_a}_{Demand\,(D)} = R_R^{-1/k} \underbrace{\eta_{S_a,C} e^{-\frac{1}{2} k \beta_{S_a,C}{}^2}}_{Capacity\,(\varphi C)}$
PSDM Based Assessment	$R_R = \left(\frac{^{P_o}S_a}{S_a^{\eta_C}} \right)^{-k} e^{-\frac{1}{2}\frac{k^2}{b^2}\left(\beta_{D \mid S_a}^2 + \beta_C^2 \right)}$	$\underbrace{\eta_{D \mid {}^{P_o}S_a} e^{\frac{1}{2}\frac{k}{b}\left(\beta_{D \mid S_a} \right)^2}}_{Demand\,(\gamma D)} = R_R^{-b/k} \underbrace{\eta_C e^{-\frac{1}{2}\frac{k}{b}(\beta_C)^2}}_{Capacity\,(\varphi C)}$

Risk-Informed Design and Evaluation Framework

Hazard vs. Failure

Conventional Structures

$$P_H = P_F$$

Nuclear Facility Structures

$$P_H > P_F$$

$$\frac{\phi C}{R_R^{\frac{b}{k}}} > \sum \gamma D$$

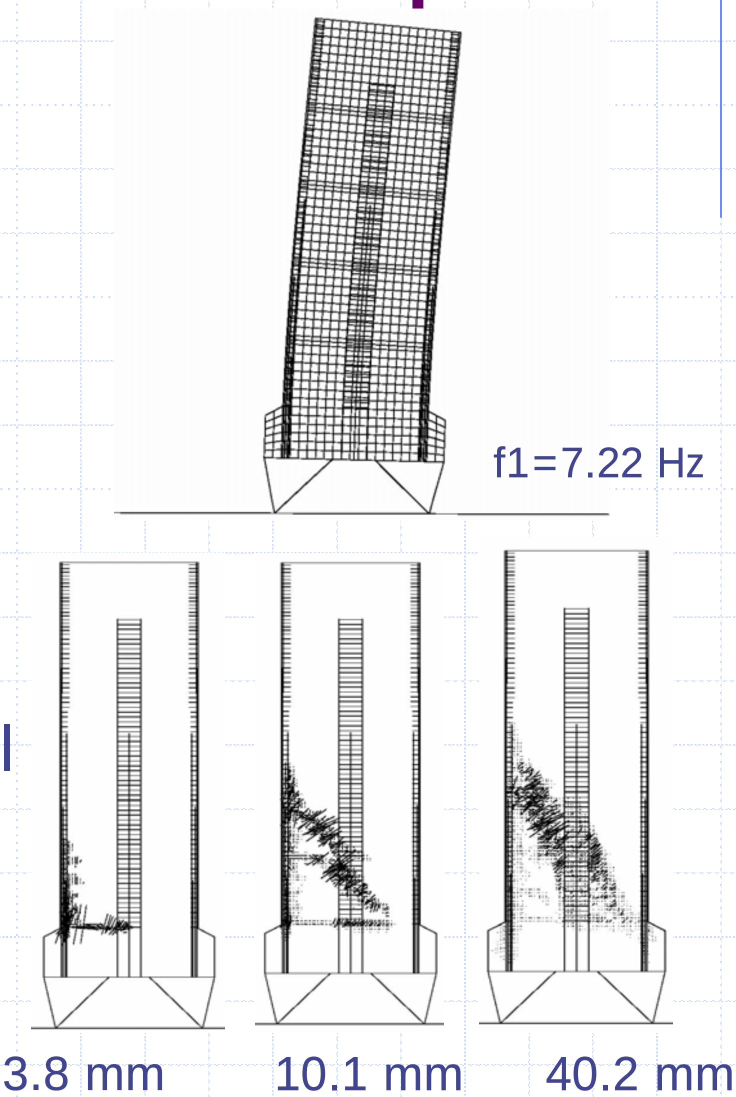
Design Equation

Simulation Needs

- Reduce epistemic uncertainty by improving our knowledge of how structures respond to earthquakes
- Reduce aleatory uncertainty by:
  - Improving estimates of seismic hazard
  - Measuring randomness in demand and capacity
- Formulate risk-informed evaluation framework:
  - Determine acceptable levels of risk reduction for performance levels relevant to nuclear facility structures

A CAMUS Shear Wall Example

- TNO DIANA 8.1
- 2-D shell-element model
- Included:
  - Shaking table model
  - Restraint provided by floor slabs
  - Embedded reinforcement
  - Interface elements to model construction joints

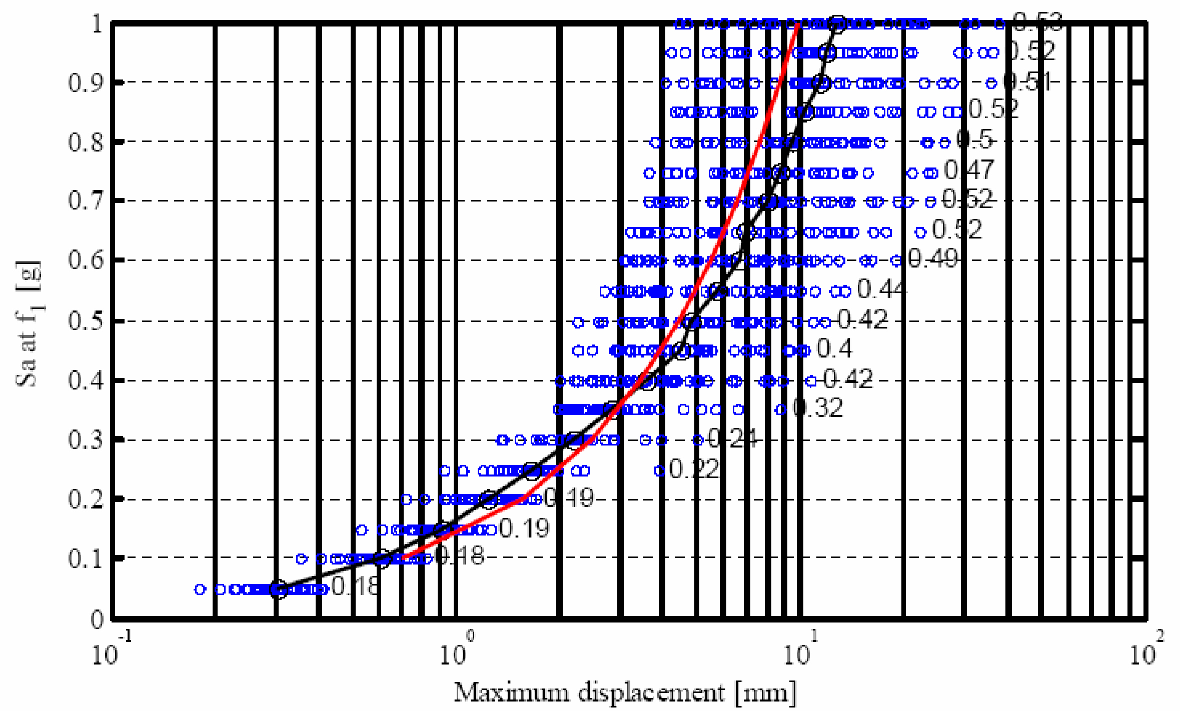


FEMA-356: Deterministic Acceptance Criteria

$\theta\,[rad]$	demand	IO	LS	CP
Run 1	0.0014	0.002	0.004	0.008
Run 2	0.0005	0.002	0.004	0.008
Run 3	0.0021	0.002	0.004	0.008
Run 4	0.0017	0.002	0.004	0.008
Run 5	0.0045	0.002	0.004	0.008

Run 5: IO and LS limit states not satisfied
(IO – immediate occupancy)
(LS – life safety)

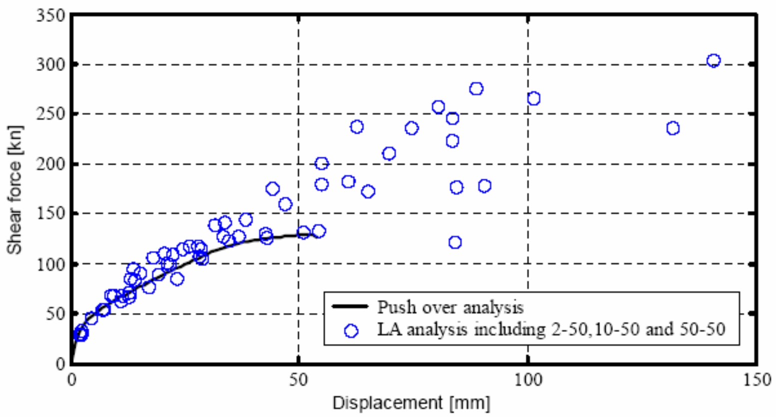
Probabilistic Demand Analysis

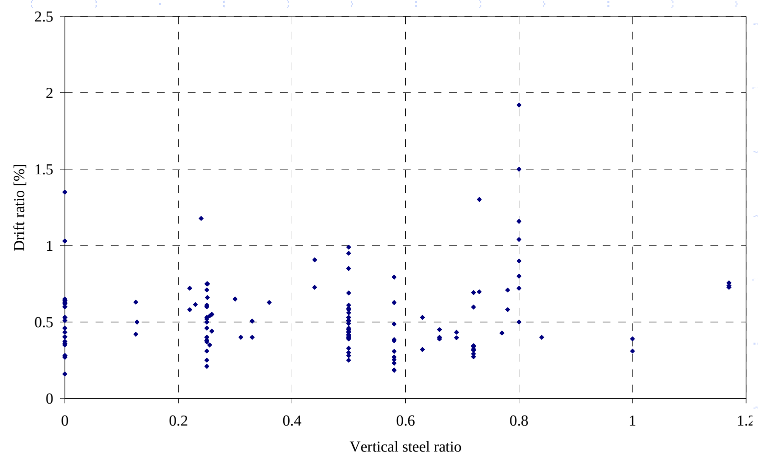


- A suite of representative ground motions
- Incremental Dynamic Analysis method
- Obtain median demand and dispersion

Probabilistic Capacity Analysis

- Done using:
  - Numerical models of the wall
  - Analysis of experimental data from tests on similar walls
- Provides a good estimate of the median capacity and dispersion





Risk-Informed Approach

- Computing risk reduction afforded by the CAMUS wall is now possible
  - This value is about 5 for the considered (Western Europe) seismic risk environment and the structural collapse limit state
- Finding: the wall is not adequate for PC-3 and PC-4
  - We know by how much
  - We know where reducing uncertainty will be most effective

Conclusion

- Modern structural design is based on a probabilistic consideration of failure:
  - Nuclear facility design provisions are formulated on the structure level
  - Conventional structures design provisions are formulated on the element level
- It is possible to formulate a unified, risk-informed design approach
- The unified approach enables using advances in earthquake engineering of conventional structures for seismic design and evaluation of nuclear facility structures

Thank you!

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